



TITLE:

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CITATION:

Matsusaka, Shuji ...[et al]. Bubbling behavior of a fluidized bed of fine particles caused by vibration-induced air inflow.. Scientific reports 2013, 3: 1190.

ISSUE DATE:

2013-02

URL:

<http://hdl.handle.net/2433/174326>

RIGHT:

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Bubbling behavior of a fluidized bed of fine particles caused by vibration-induced air inflow

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Received
4 October 2012

Accepted
15 January 2013

Published
1 February 2013

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We demonstrate that a vibration-induced air inflow can cause vigorous bubbling in a bed of fine particles and report the mechanism by which this phenomenon occurs. When convective flow occurs in a powder bed as a result of vibrations, the upper powder layer with a high void ratio moves downward and is compressed. This process forces the air in the powder layer out, which leads to the formation of bubbles that rise and eventually burst at the top surface of the powder bed. A negative pressure is created below the rising bubbles. A narrow opening at the bottom allows the outside air to flow into the powder bed, which produces a vigorously bubbling fluidized bed that does not require the use of an external air supply system.

Granular materials and fluids exhibit vastly different behaviors due to differences in their discreteness and continuity^{1–3}. As demonstrated through experiments using noncohesive coarse particles, each solid in a granular material moves independently when a vibration is applied, which results in the observation of unusual behaviors, such as convection^{4–7}, bubbling^{8–10}, granular waves^{11–13}, oscillons¹⁴, and segregation^{15,16}. The convection and bubbling behaviors, which display complex but structured particle movements, have the potential to be used in numerous applications, such as fluidization and mixing. Granular material studies have been conducted using noncohesive particles with diameters that are larger than several hundred micrometers. In general, fine particles have been found to be more useful than coarse particles because fine particles have larger specific surface areas, which prove effective for microscopic surface activities and homogeneity. However, the adhesive and cohesive properties of fine particles make them difficult to handle in a gaseous form.

The main attractive interaction forces between particles are van der Waals, electrostatic, and liquid bridge forces. These forces are theoretically proportional to the first or second power of the particle diameter^{17,18}, whereas gravity is proportional to the cube of the particle diameter. Consequently, the interaction forces are dominant in smaller particles, and gravity does not induce the flow of these particles.

The coupling of aeration and vibration has been attempted for the fluidization of these types of cohesive fine particles^{19–21}. In addition, an external air supply system is thought to be essential to achieve fluidization of these particles. However, our research reveals that the use of higher frequency vibrations without an external air supply system can cause cohesive fine particles to exhibit vigorous bubbling in a powder bed. In this manuscript, this newly found phenomenon is presented, and the bubbling mechanism in the fine powder bed is elucidated experimentally.

Results

Horizontal vibration system. A horizontal vibration system was used to study the bubbling behavior in the fine powder bed. Figure 1 shows a schematic diagram of the experimental setup, which consists of a glass tube (i.d.: 22 mm, o.d.: 25 mm, $l = 210$ mm), a bottom plate (o.d.: 30 mm), a rectangular solid ($w = 8$ mm, $d = 12$ mm, $h = 50$ mm), piezoelectric vibrators, and a vibration control system (IMP. Co., Ltd.). The glass tube was placed vertically such that a gap of 50 μ m remained between the bottom plate and the bottom end of the tube. To independently apply the horizontal vibrations, the two vibrators were attached to the bottom plate and the tube wall at a distance of either 100 or 40 mm from the bottom end of the tube. The rectangular solid was attached to the center of the bottom plate to effectively propagate the external vibrations into the powder bed. The glass tube and the bottom plate were subjected to antiphase vibrations. The frequency and amplitude of the vibrations were 300 Hz and 60 μ m, respectively.

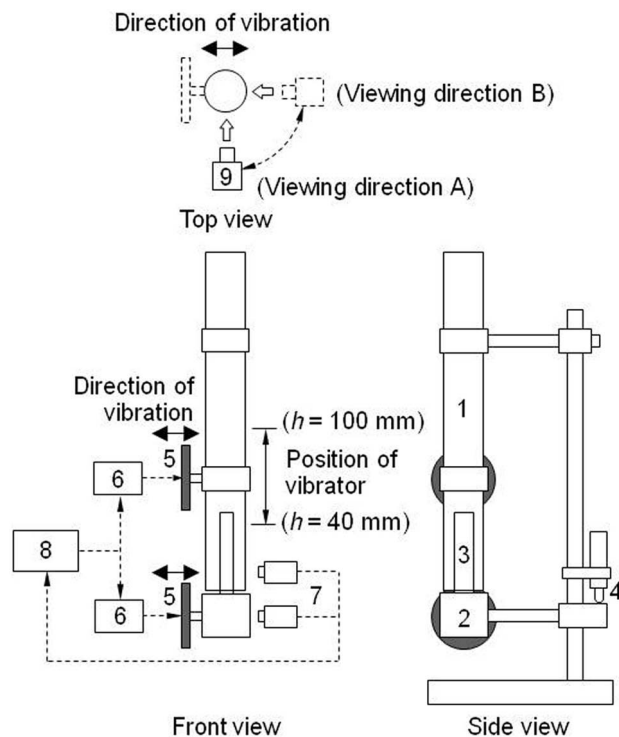


Figure 1 | Experimental setup. 1) Glass tube, 2) bottom plate, 3) rectangular solid, 4) screw micrometer, 5) piezoelectric vibrator, 6) amplifier, 7) laser vibrometer, 8) computer, 9) video camera.

Multilayered structure of bubbles. A convective flow was observed in the powder bed as a result of horizontal vibrations, i.e., the particles in the center moved downward, whereas those near the side walls moved upward when the vibrations were applied in the normal direction. Figure 2a shows a series of images of the oscillating powder bed in the glass tube when the vibrator was attached 100 mm from the bottom of the glass tube (Supplementary video S1). A multilayered structure of bubbles was formed in the upper part of the powder bed. The upper bubbles in this structure were extended horizontally. A similar multilayered structure also occurred on the back side of the glass tube. Small bubbles were constantly generated at a depth of 25 ± 5 mm from the surface of the powder bed. These bubbles rose to the top and eventually burst at the surface of the powder bed. The thin powder layer between the bubbles frequently broke, which led to the coalescence of two bubbles to form a larger bubble. Consequently, the number of bubble layers varied within a given range. This regular arrangement of bubble layers sharply contrasts with the results obtained in previous work using coarse bubbles because multiple bubble layers have not been previously observed⁸.

Figure 2b shows the number distribution of bubbles in the multilayered structure, which ranged from four to seven and had a mode value of six. The interval between the bubble layers was several millimeters. Figures 2c and 2d show the time interval distributions of the generation and coalescence of bubbles, respectively. The bubbles were generated in intervals of less than 0.3 s with a mode value of 0.1 s. The bubble coalescence typically occurred in very short intervals. These specific features in the multilayered structure of bubbles always appeared when vibrations were applied.

Vigorous bubbling in a bed of fine particles. The vibrator was attached 40 mm from the bottom end of the tube. When vibrations were applied, a multilayered structure of bubbles was soon observed. A few seconds later large bubbles formed near both side

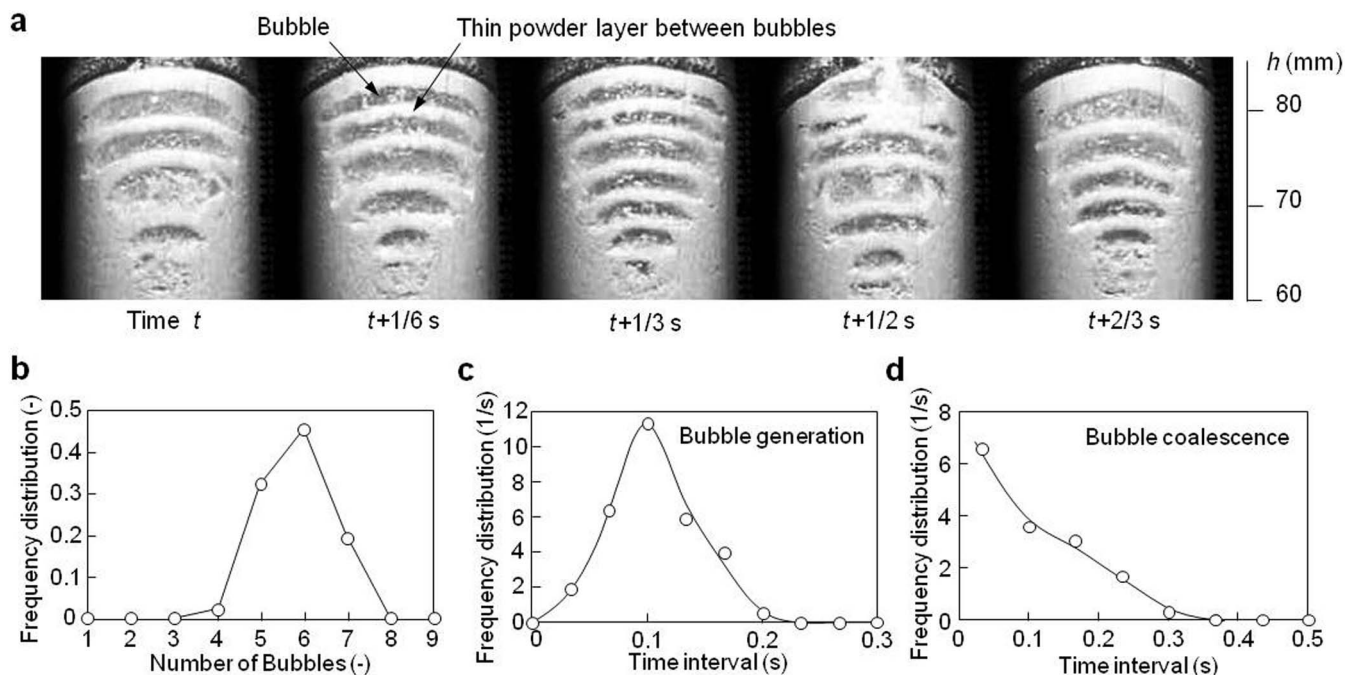


Figure 2 | Bubbling behavior in a powder bed of fine particles that is subjected to vibration. (a) A series of images of the oscillating powder bed in the glass tube when the vibrator is attached 100 mm from the bottom end of the glass tube (viewing direction B in Fig. 1). Small bubbles, which are constantly generated at a depth of approximately 25 ± 5 mm from the surface of the powder bed, rise to the top and produce a multilayered structure of bubbles. The thin powder layer between the bubbles often breaks, which causes two bubbles to coalesce and form a larger bubble. (b) Distribution of the number of bubbles in the multilayered structure. (c) Distribution of the time interval of the generation of bubbles. (d) Distribution of the time interval of the coalescence of bubbles. Both of the distributions in (c) and (d) were obtained through the analysis of numerous images.

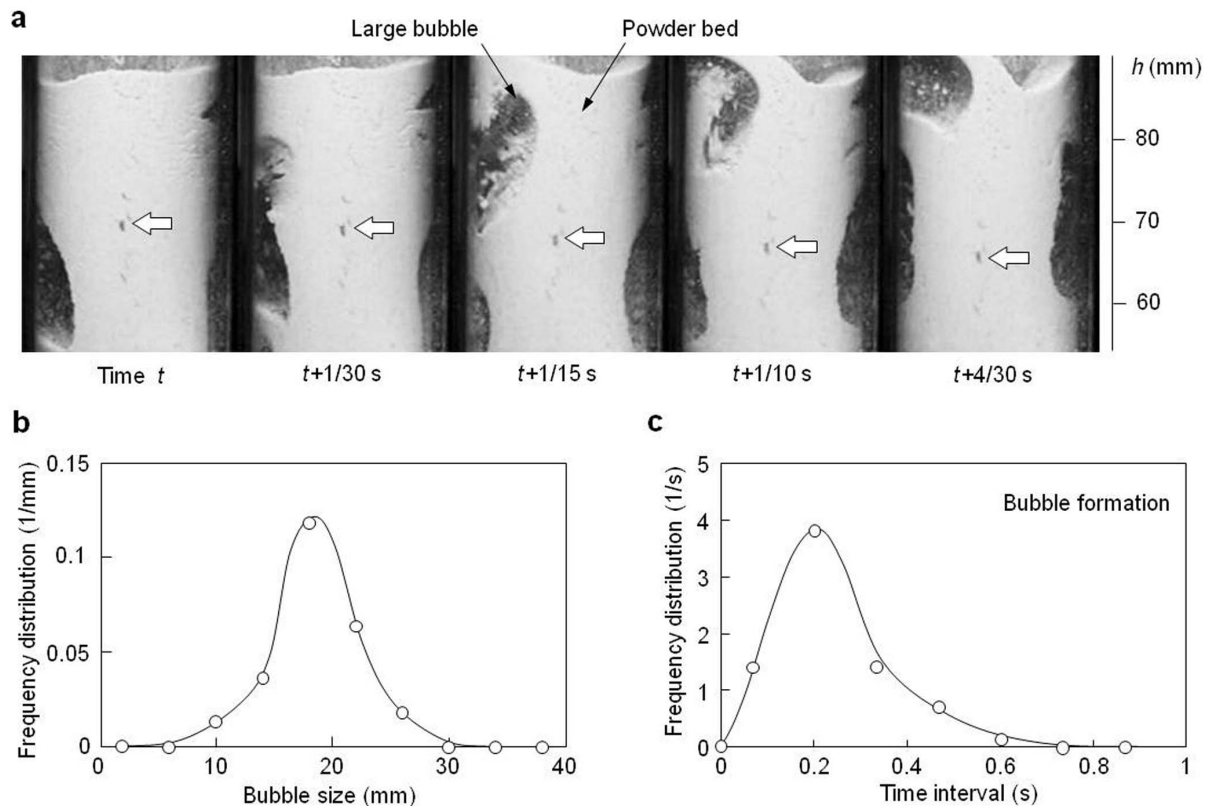


Figure 3 | Bubbling behavior that is caused by the vibration-induced air inflow. (a) A series of images of the oscillating powder bed in the glass tube when the vibrator is attached 40 mm from the bottom of the glass tube (viewing direction A in Fig. 1). Large bubbles, which form near both side walls, rise rapidly and burst at the top surface of the powder bed. The white arrows denote the trajectory of a tracer particle that moved downward at a low velocity. (b) Distribution of the bubble size in the vertical direction measured 50 mm from the bottom of the tube. (c) Distribution of the time interval of bubble formation, which was obtained through the analysis of numerous images.

walls and rose at a velocity of several hundred millimeters per second before bursting at the top surface of the powder bed. Figure 3a shows a series of images of the vigorous bubbling in the oscillating powder bed in the glass tube (Supplementary video S2). Each large bubble

was independent, and the bubbling state differed from that observed in the multilayered structure (Fig. 2a). The inflow of air from the bottom of the tube generated larger bubbles. The air that was forced out of the powder layer by the convective flow was also mixed with

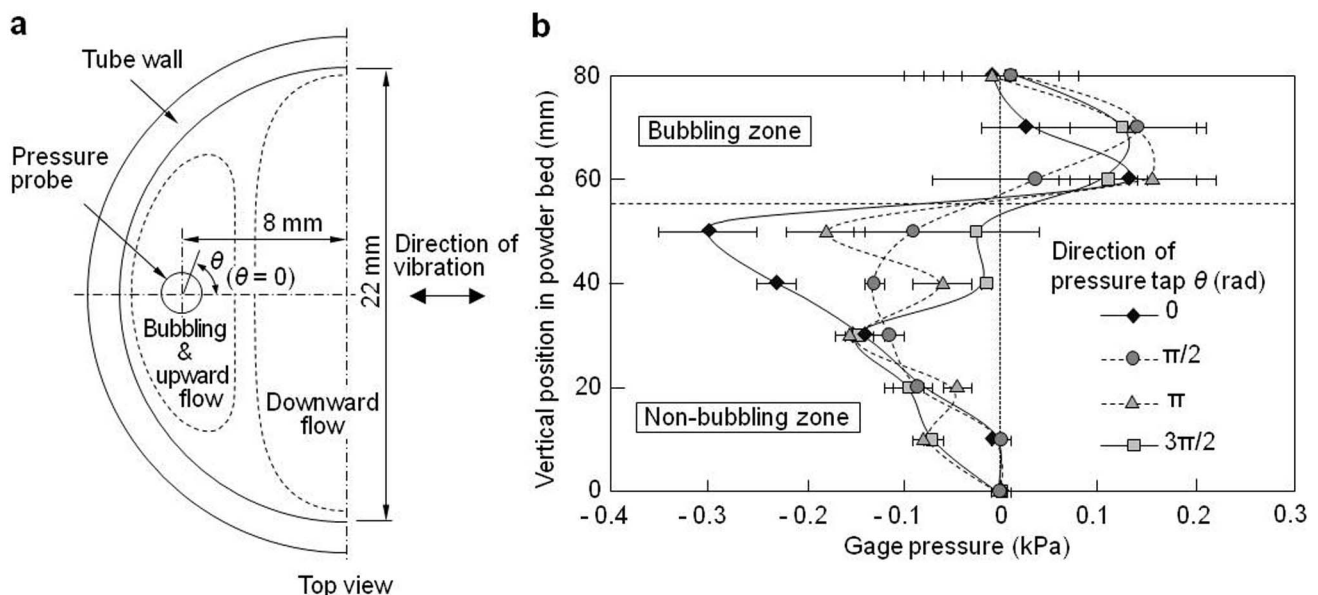


Figure 4 | Measurement of the air pressure in the powder bed. (a) Top view of the measurement positions and directions, i.e., $\theta = 0, \pi/2, \pi$, and $3\pi/2$ rad. The broken lines indicate the zones of upward flow with bubbling and the zones of downward flow. The air pressure is measured at multiple positions, including the bubbling zone near the tube wall. (b) Distribution of the air pressure in the vertical direction when the vibrator is attached 100 mm from the bottom end of the glass tube.

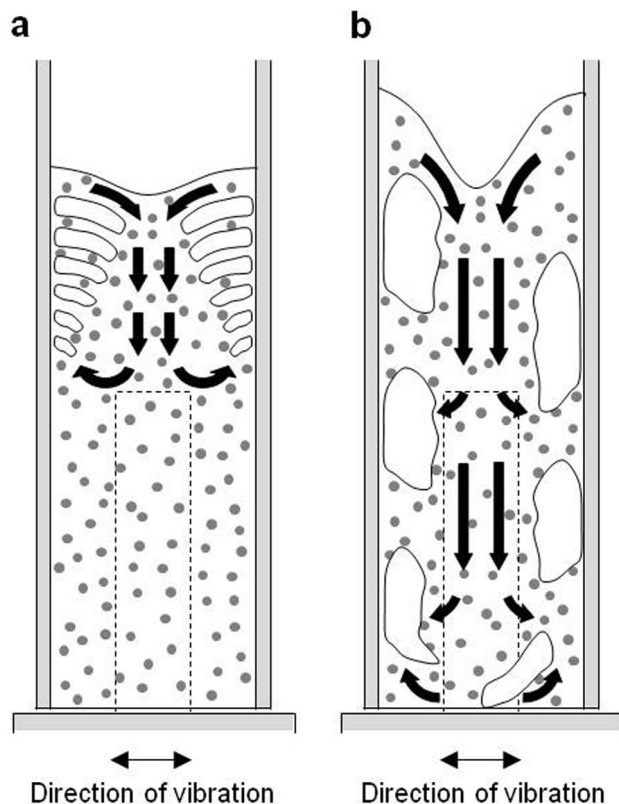


Figure 5 | Illustration of the two types of bubbling and convective flow (viewing direction A in Fig. 1). (a) A multilayered structure of bubbles is formed by convective flow and compression caused by vibration ($h = 100$ mm). (b) Vigorous bubbling is caused by vibration-induced air inflow from the bottom of the tube ($h = 40$ mm).

the bubbles. The air flow rate from the top of the tube was $5 \text{ cm}^3/\text{s}$. The convective flow caused the particles in the center to move downward. The trajectory of a dark tracer particle, which is denoted by white arrows in the images, shows that the particles had a downward flow velocity of several tens of millimeters per second. Figure 3b shows the bubble size distribution in the vertical direction, which was measured 50 mm from the bottom end of the glass tube. The maximum bubble size was 30 mm, which is much larger than that of the bubbles in the multilayered structure. Figure 3c shows the time interval distribution of the bubble formation: the distribution range was less than 0.8 s and had a mode value of 0.2 s. These values are larger than those shown in Figure 2c.

Discussion

To clarify the mechanism by which the above phenomenon occurs, the local air pressure was measured near the tube wall at vertical intervals of 10 mm. Figure 4a shows the positions and directions of the air pressure measurements, and Figure 4b shows the distributions of the gauge pressure. The vibrator was attached 100 mm from the bottom of the tube during these experiments. Although the data fluctuated slightly due to convective flow and bubbling, the same specific features always appeared: the gauge pressure was positive from 55 to 80 mm and negative from 0 to 55 mm. At the top and bottom of the powder bed, which were open to the atmosphere, the gauge pressure was zero. The positive and negative pressures in the vertical direction corresponded to the bubbling and nonbubbling zones, respectively.

The correspondence between the pressure and the bubbling zones can be explained as follows (Fig. 5a). When convective flow occurs in

the powder bed as a result of vibrations, the upper powder layer with a high void ratio moves downward and is compressed, which forces air out of the space around the particles. The air pressure thus becomes positive. The small bubbles that are formed in the powder bed coalesce to become larger bubbles, which rise and burst at the surface of the powder bed. When bubbles with a positive pressure rise, a negative pressure is created below them.

In this study, we considered a new concept of bubbling in a powder bed (Fig. 5b). If a larger negative pressure can be created at the bottom of the powder bed, the pressure difference will cause the outside air to enter the powder bed through a small gap between the glass tube and the bottom plate. The larger negative pressure region can be expanded to the bottom of the powder bed by lowering the position of the vibrator that is attached to the glass tube.

As shown in Figure 3a, the adjustment of the height of the vibrator that was attached to the glass tube allowed vigorous bubbles to form in the powder bed of fine particles. Furthermore, the vibrator height affected the region of the convective flow in the powder bed and thus significantly influenced the bubbling behavior, i.e., the difference between the bubbling in a multilayered structure and the vigorous bubbling observed with the inflow of air. This novel fluidized bed that uses a vibration-induced air inflow system should prove useful for various applications, including closed fluidized systems and open fluidized systems in fine industries.

Methods

The sample that was used in the experiments was an alumina powder with a mass median diameter of $8 \mu\text{m}$ and a particle density of 4000 kg/m^3 . The initial bed height was set at 80 mm to generate large convective flow and create a large negative pressure under the vibrations. A pressure probe with a tap hole on one side was used to measure the local air pressure in the powder bed. The air flow rate that passed through the powder bed from the bottom was determined by measuring the volume of the air that flowed out of the top of the tube per unit time. A small amount of tracer particles was also fed into the powder bed to observe the particle behavior through the glass tube wall.

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Acknowledgements

This research was supported by the program to promote a career path for research personnel of academia and accelerate technology transfer, JST.

Author contributions

S.M. developed the theory and S.M. and M.Y. designed the experiments. M.K., M.M., M.I.

and M.Y. performed the experiments and analyzed the data. All of the authors contributed to the writing of the manuscript.

Additional information

Supplementary information accompanies this paper at <http://www.nature.com/scientificreports>

Competing financial interests: The authors declare no competing financial interests.

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How to cite this article: Matsusaka, S., Kobayakawa, M., Mizutani, M., Imran, M. & Yasuda, M. Bubbling behavior of a fluidized bed of fine particles caused by vibration-induced air inflow. *Sci. Rep.* **3**, 1190; DOI:10.1038/srep01190 (2013).